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A Contribution of Photon Hadronic Component in the Leptoproduction Charmed Structure Function at Large x and Q^2

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Abstract

We calculated the contribution of the photon hadronic component in the charmed structure function of the leptoproduction. The contribution comes from scattering of the c quarks of the virtual photon on the quarks and gluons of the proton. Comparison of our calculations with the measurements of the charm production in μ^+p-scattering by EMC shows, that contribution of resolved photon can explain the excess of EMC data over the predictions of the photon-gluon fusion model at large momentum transfers. Thus, one does not need to use a non-perturbative admixture of the charmed quarks in the proton wave function ("intrinsic charm") to describe such an excess in EMC data.

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1 Introduction

Investigations of heavy flavours production at high energies remains to provide a very important tool for qualitative and quantitative test of the QCD and for study of the internal hadron structure. Despite the impressive experimental and theoretical results obtained during last decade due to, mainly, experiments at the electron-proton collider HERA, there still exist uncertainties in the interpretation of data on the charm production in hadron-hadron and lepton-hadron collisions. These uncertainties relate to the details of the quark structure of hadrons, in first turn the proton. One of these problems is the problem of "intrinsic charm" (IC) of the proton [1], i.e., the question about the presence in the wave function of the hadron a visible ($\approx 1\%$) non-perturbative admixture of the charmed quarks with hard, "valence-like" distribution over their longitudinal momenta. Investigations at HERA have been performed at small values of x, where the main contribution comes from the photon-gluon fusion mechanism (PGF). But small values of the variable x describe the space scales much greater, than the proton size and, therefore, the study of those kinematical regions gives information about the structure of the QCD vacuum itself, rather than about the internal structure of the proton. To understand the internal structure of the proton it is necessary to study the proton charmed structure function at large values of x. But the geometries of ZEUS and H1 set-ups do not allow to study efficiently the charm production processes in the very forward region at relatively small momentum transfers, where the cross-section of the ep scattering is maximal. The planned HERA upgrade will increase few times the collider luminosity and, perhaps, this increase will allow to collect sufficient statistics at large momentum transfers for the experimental study of the charm production in the range of large values of x. But at present this problem is not well investigated.

The theoretical consideration of the "intrinsic charm" problem is based on the following simple points. The wave function of the proton can be expanded over the colourless eigenstates of free Hamiltonian $|uud>$, $|uudg>$, $|uudq\bar{q}>$, $\ldots$. During sufficiently long time the proton can consist of Fock states of an arbitrary complexity, including a pair of charmed quarks. In the proton rest frame the life-time of such a fluctuation τ has the order of the nuclear time $\sim R_h$, where R_h is the hadron size. Charmed quarks are heavy objects and their life-time is much less than that of light partons. Therefore, in average, the admixture of the heavy quark pairs in the proton wave function is to be small, $\sim (m_q/m_Q)^2$, that is, by factor $\sim 10^2$ less than life-time of a fluctuation containing light partons only. Additionally, because of c quarks are massive it turns out that their momentum distributions are to be much harder than the distribution of the light sea partons [1, 2]. The existence of the fluctuation, containing heavy quarks is a natural consequence of the field theory. But the important guess is that quantum fluctuations of the hadron wave function containing charmed quarks appear due to self-interaction of the colour field, ensuring the non-perturbative origin of the intrinsic charm distribution. In this case the structure of the hadron Fock states with charm can be considered independently of hard interactions.

Estimating the level of the charmed quarks admixture in the proton, they usually suppose that experimental indications on the intrinsic charm exist in μp collisions [3] and in hadronic collisions data [4, 5], where deviations from the photon-gluon and parton-parton fusion models predictions have been observed. But the experimental situation is sufficiently uncertain. The original work [1] was motivated by ISR data [4], where a very large yield of the charm had been obtained, at least, order of magnitude larger than it was expected in the model of the parton-parton fusion. A critical comparison of the ISR results against the contemporary fixed-target data can be found in the review [6]. Later experiments (though carried out at lower energies), did not contradict so dramatically to the theoretical expectations (see, e.g., [7]). In paper [8] an attempt has been taken to co-ordinate the ISR data with the parton-parton fusion predictions. There has been considered the process of the "charm excitation", based on the guess about 0.5% admixture of the charmed quarks in the proton, which admixture leads to the hard scattering of the charmed quarks. Due to large cross section of the hard scattering (strictly speaking, this cross section diverges) and to its stronger dependence on reaction energy, it was shown [8], that ISR data can be described in framework of the charm excitation model. At the same time this model does not predict visible contribution in the charm yield at lower energies.

Experimental data on longitudinal distributions of charmed particles and on asymmetry of their production can be reproduced with acceptable accuracy without the "intrinsic charm" hypothesis, only by reasonable variation of parameters of string hadronization model [9, 10].

The interpretation of the data on J/ψ particle production is also contradictory. In the experiment NA3 [5] in pion-nuclear collisions at energy 280 GeV definite indications on the presence of an additional mechanism of hard J/ψ production were obtained. This additional contribution at the level of 20% of the total of J/ψ production cross section is well described by the modified model of the intrinsic charm [2], but the guess about so large contribution does not look very realistic. It was noted in papers [11, 12], that intrinsic charm can also explain a larger than it was expected yield of fast correlated pairs of J/ψ particles, as well as anomalous polarization of J/ψ's, probably observed in NA3 experiment. At the same time predictions of the intrinsic charm model directly contradict to data on J/ψ production in proton-nuclear collisions at energy 800 GeV [13] (see [14]).

Note, that the admixture of the charmed quarks in the proton at level of 1% leads to total cross section of charm production in nucleon collisions of order of few hundreds microbarn in conflict to the bulk of the experimental data on open charm production in hadronic interactions.

Doing any theoretical analysis of the hadronic data it is necessary to keep in mind, that the main contribution in the charm production in hadronic collisions is led by the gluon-gluon fusion $gg \to c\bar{c}$. At the same time the direct measurements of the gluon distributions are impossible. To extract the gluon distributions from data they use either charm production calculations based on the gluon-gluon and photon-gluon mechanisms, which contributes in the small x_F range, or sufficiently involved methods based on the guess that the main contribution in the QCD evolution is driven by the gluons. Due to this fact the extraction of an additional mechanism of charm production at level of $(0.5-1)\%$ can not be reliable.

In fact, the only experimental data, which allow to perform sufficiently reliable check of the presence of the intrinsic charm in the proton are the EMC measurements of the charm photoproduction in μ^+p collisions at energy 250 GeV. In early papers on the EMC data analysis they used old, harder parametrizations of the gluon distributions in the proton. In particular, in the first analysis carried out by EMC the scaling gluon distribution $G(x) \sim (1-x)^5$ has been used, which gave the deviation from the photon-gluon mechanism predictions at level of about 0.3% with sufficiently large error of this value. Modern and, as a rule, softer parametrizations of the gluon distribution, lead, naturally, to larger contribution of the intrinsic charm in the EMC data [15, 16, 2]. Thus, the intrinsic charm contribution, extracted from analysis of the EMC data varies from 0.3% [3, 17] to, approximately, 0.9% [16, 2]. In paper [16], where the most careful calculations of the contribution of the photon-gluon fusion have been done, it was shown that at small energy transfers the intrinsic charm contribution is absent within the experimental errors.

Due to existence of the hadronic structure of photon [18, 19, 20] the total charm production cross section in the leptoproduction should also include the interactions of the partons from the virtual photon with the proton. Such a contribution of the hard scattering of c quarks from the virtual J/ψ meson calculated in framework of the vector dominance model in [21], allowed to reproduce with a good accuracy the results of ZEUS experiment on D^* mesons production at large transverse momenta. Despite the fact that the scattering processes are to the second order by α_s, they can produce quite visible effects due to divergence of the parton-parton scattering cross sections at small angles. Therefore, it is natural to expect, that the hadronic component of the resolved photon can also give a visible contribution in the charmed structure function, measured by EMC in the range $Q^2 \geq 40$ GeV^2, where the indications on the deviation of the experimental data from the photon-gluon predictions exist.

In present work we have calculated the contribution of the hadronic component of the photon and the contribution of the standard mechanism of the photon-gluon fusion in the charmed structure function, measured in EMC experiment. The calculations performed in present work show, that it is not necessary to consider the intrinsic charm admixture in the proton to interpret the EMC data.

2 The basic outline of the model

2.1 Charm in the hadronic component of the photon

In the deeply inelastic processes with hadrons the measured physical quantity is the hadron structure function $F_2(x, Q^2)$. The charm production cross section in electroproduction $Lp \to c$, expressed through the structure function $F_2^c(x, Q^2)$ is:

$$d\sigma(lp \to c) = \frac{2\pi\alpha^2}{xQ^4} \left[1 + (1-y)^2\right] F_2^c(x, Q^2)\, dx\, dQ^2 \,, \tag{1}$$

and in the equivalent photon approximation [22] it can be expressed through the cross section of the γp interaction $\sigma(\gamma p \to c)$ and the flux of the equivalent photons $n_\gamma(x, Q^2)$ as:

$$\begin{aligned} d\sigma(lp \to c) &= dn_\gamma(x, Q^2)\, \sigma(\gamma p \to c)\,, \\ dn_\gamma(x, Q^2) &= \tfrac{\alpha}{2\pi} \left[1 + (1-y)^2\right] \tfrac{dx}{x} \tfrac{dQ^2}{Q^2}\,. \end{aligned} \tag{2}$$

That is, the charmed structure function is connected to the charm photoproduction cross section as the following:

$$F_2^c(x,Q^2) \; = \; \frac{Q^2}{4\pi\alpha}\,\sigma(\gamma p \,\to\, c)\,. \tag{3}$$

The hadronic structure of the photon can also be described by the photon structure function $F_2^\gamma(x,Q^2)$, depending on Bjorken variable x and on the momentum transfer squared Q^2 [18]. The structure function $F_2^\gamma(x,Q^2)$ is usually subdivided in two terms – perturbative (so called "anomalous") and non-perturbative ("hadronic") parts. Such a subdivision of $F_2^\gamma(x,Q^2)$ is valid not only within the framework of the naïve quark parton model (QPM), but also in the next-to-leading order of QCD [18, 19]. The perturbative part is led by direct interaction $\gamma \,\to\, q\bar{q}$ and can be completely calculated in the framework of the perturbation theory. The contribution of this part in QPM is proportional to $\ln Q^2$ and dominates at $Q^2 \,\to\, \infty$. The non-perturbative part of $F_2^\gamma(x,Q^2)$ is completely analogous to the ordinary structure function of hadrons. In the framework of the naïve QPM this part does not depend on Q^2. The QCD evolution of F_2^γ differs from the evolution of the hadron structure function only due to the existence of the perturbative part in the F_2^γ thus being described by the inhomogenious DGLAP equations. To calculate the QCD evolution of the non-perturbative part, similarly to the hadron case, it is necessary to set the initial conditions at some value of momentum transfer Q_0. As a rule, choosing the initial conditions for the parton distributions in the photon at $Q_0^2 \,\approx\, 1$ GeV^2 they suppose, that the hadronic part of $F_2^\gamma(x,Q_0^2)$ can be derived from the vector dominance model (VDM), postulating the transition $\gamma \,\to\, \rho^0$ to describe the interaction of the photon with hadrons. The parton distribution in ρ^0 meson are obtained using the parton distributions in pions known from the experiment. For better description of the experimental data the simple VDM has been extended by the obvious way by inclusion of iso-scalar vector mesons ω, ϕ. The extention of the VMD by inclusion of heavier mesons from J/ψ family is not, normally, used because of large masses of J/ψ mesons and the charm content in the photon is described by the evolution of light partons and by the perturbative term $\gamma \,\to\, c\bar{c}$ [20, 23]. But, as it has been shown in [20], in the range $Q^2 \,\leq\, 50$ GeV^2 charm must not be considered as a light quark and the evolution equations must be solved for three light flavours only. This is because of the fact that in the threshold region $Q^2 \,\sim\, 4m_c^2$ the charm production must be described by the Bethe-Heitler process $\gamma\,\gamma \,\to\, c\bar{c}$ and by its analogue, the photon-gluon fusion process $\gamma\, g \,\to\, c\bar{c}$ in case of leptoproduction. On the other hand, in paper [24] from comparison of the QCD evolution predictions for F_2^γ to experimental data the conclusion has been made that even for evolution of light quarks the perturbative region in case of the photon starts at $Q_0^2 \,\approx\, 5$ GeV^2, not at $Q_0^2 \,\approx\, 1$ GeV^2. Thus, in present work we use the generalized model of vector dominance (GVMD), taking into account also non-perturbative transitions of the photon to J/ψ mesons, which become possible beyond the J/ψ production threshold.

Then, it is suitable to represent the wave function of the hadronic component of the photon as following:

$$|\gamma_{had}> = \sum_V \sqrt{\frac{4\pi\alpha}{f_V^2}}\,|V> + |\gamma_{pert}^{(c)}> + \sum_q |\gamma_{pert}>, \tag{4}$$

where terms $|\gamma_{pert}>$ and $|\gamma^{(c)}_{pert}>$ take into account the perturbative contributions of the processes $\gamma \to q\bar{q}$ and $\gamma \to c\bar{c}$, respectively, and vector mesons $V = \rho,\, \omega,\, \phi,\, J/\psi$ describe the non-perturbative contribution in the hadronic component of the photon. The constants, characterizing the contributions of vector mesons are [23]:

$$
\begin{aligned}
f_\rho^2/4\pi &\approx 2.20\,, \quad f_\omega^2/4\pi \approx 23.6\,, \\
f_\phi^2/4\pi &\approx 18.4\,, \quad f_\psi^2/4\pi \approx 11.5\,.
\end{aligned}
\tag{5}
$$

At presence of the hadronic structure of photon, the interactions of its hadronic component can be described in analogue to the ordinary hadrons as interactions of the partons from the photon with the colliding particle. In the framework of the parton model the cross section of any process is a sum of the cross sections of all elementary subprocesses, weighted by distribution functions of partons, participating in these subprocesses. If charmed quarks exist in the proton ("intrinsic charm") the leading over strong interaction constant process at moderate momentum transfers is the scattering of the lepton on charmed quark of the proton $lc \to lc$. The photon-gluon fusion process $\gamma\, g \to c\bar{c}$ has the next order in α_s, but its contribution dominates due to the fact that gluons carry almost half of the proton momentum. Thus, one can expect that the contribution in the charm photoproduction comes from four processes - the absorption of the virtual point-like photon by c quark of the proton, the photon-gluon fusion, the scattering of the c quark from virtual photon on light partons of the proton and the scattering of light partons from the resolved photon on c quarks of the proton. Therefore, the total cross section of the charm production can be written as:

$$
\sigma(\gamma p) \;=\; \sigma^{IC} + \sigma^{PGF} + \sigma^{\psi} + \sigma^{(c)} + \sigma^{(q)} \tag{6}
$$

Here, σ^{IC} defines the absorption of the virtual photon by c quark of the proton; the cross section σ^{PGF} describes the photon-gluon process $\gamma g \to c\bar{c}$. The second pair of terms in (6) comes from scattering of c quarks from the photon on the partons of the proton and $\sigma^{(q)}$ is led by scattering of light partons from the photon on c quark of the proton. The light partons of the photon can originate from the non-perturbative part (light vector mesons ρ, ω, ϕ), as well as from perturbative part $|\gamma_{pert}>$. It follows from (5), that the contribution of J/ψ meson in the hadronic component of the photon is about 16% of the contribution of the light vector mesons. At the same time the contribution of scattering of light partons from photon on charmed quarks from the proton $\sigma^{(q)}$ is proportional to the level of admixture of the charmed quarks in the proton, $N_{IC} \leq 0.01 << 1$, and can be neglected. The term $\sigma^{(c)}$ describes the contribution of the scattering of the *"perturbative"* c quark from the photon on partons of the proton. We denoted as *"perturbative"* those c quarks of the photon, which appear either due to anomalous part of the photon hadronic component or to QCD evolution of original light partons. Thus, the distribution of such c quarks can be obtained in the framework of the perturbation theory [20, 25] and, as quoted above, this contribution is limited by the range $Q^2 \geq 50$ GeV^2. Using the parametrization [26] for the distribution of the *"perturbative"* c quarks[1], we have verified,

[1]Technically, we used the respective subroutines from the package PYTHIA 6.1 [27].

that the contribution of the perturbative term $\sigma^{(c)}$ can be safely neglected in the kinematical range considered in present work, $Q^2 \leq 80$ GeV^2.

The contributions in the charm production come also from the processes of parton-parton fusion $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$, completely analogous to the processes, describing the charm production in hadronic collisions. But, these processes have finite total cross sections and their contribution in the charm yield is small in comparison to the photon-gluon fusion process. Thus, we also drop them. Quite different situation appears for scattering processes of c quarks from J/ψ meson on light partons of the proton. In the pQCD the cross sections of these processes are divergent as $1/p_T^4$. Therefore their contributions can be significant. As the result of the above consideration we keep in (6) only terms σ^{IC}, σ^{PGF} and σ^{ψ}. Their contributions in the charmed structure function will be calculated further. The diagrams of the processes, taken into account in present work are depicted in Fig. 1.

2.2 The c quark distribution in virtual J/ψ meson

To find the non-perturbative distributions of c- and $\bar{c}$ quarks in the virtual J/ψ meson we can follow the approach developed in [2]. This approach is based on the statistical model [28] and on the work [1], allowing to take into account the masses of heavy quarks in the framework of the non-covariant perturbation theory (NPT). This approach allows to find the probability of creation of the Fock state with heavy quarks. The basic point is the fact, that we can use NPT to derive the necessary distribution. Feynman diagram is a sum over all time-ordered diagrams of the NPT. The contributions of time-disordered diagrams are proportional to the inverse powers of large hadron momentum P_h. Thus, any consideration in the framework of the parton model is being carried out in the "infinite momentum reference frame", i.e., in the reference frame, where the hadron momentum is much larger than any of characteristic mass parameters. At high energies of the colliding particles the momentum of the hadron is sufficiently large, which ensures the applicability of NPT. Only in this case the virtual configuration of Fock states, in which the proton fluctuates, can be "frozen" for the time of the interaction. If we consider the processes led by the transition of the photon into a hadron (vector meson), the life-time of the virtual hadronic fluctuation (given Fock state) is $\Delta t \sim 1/\Delta E \approx 2\,P_h/\,(M^2 - m^2)$ (P_h - the hadron momentum, m - hadron mass and M - the mass of the fluctuation) and at high energy can be large enough even for large values of the fluctuation mass M.

Expression (6) means, in fact, that different terms in (4) do not interfere. This, in turn, allows the probabilistic interpretation of the expansion (4). Namely, it is legitimate to assume that during the interaction time the photon is in one of the states, entering the expansion (4). In this case partons of the photon carry all the momentum of the photon (more correctly, all the momentum of the hadronic fluctuation). Due to sharp cut-off over transverse momenta of partons, it is sufficient to consider the longitudinal phase space only. We consider a hadron (or hadronic fluctuation of the photon in our case) as a statistical system, consisting of m partons, carrying in sum the quantum numbers of the hadron and its momentum. In spirit of the parton model we suppose an independent creation of each parton with relative momentum ξ according to the probability density $\rho(\xi)$. Then, in the framework of NPT the probability to find n-parton final state can be written as [2]:

$$dW^{(n)} \sim \frac{1}{\left(E_{fin} - E_h\right)^2} \delta^{(3)} \left(\vec{P}_{fin} - \vec{P}_h\right) \prod_{i=1}^{n} \rho_i(\xi_i) \frac{d\xi_i}{\xi_i}, \qquad (7)$$

where, n is the total number of partons in the considered fluctuation, $\vec{P}_h$ and E_h are momentum and energy of the hadron; $\vec{P}_{fin}$ and E_{fin} are total momentum and energy of the fluctuation, respectively. δ–function enforces the conservation of the total 3-momentum. Function $\rho_i(\xi_i)$ describes the probability to create ith parton without conservation of the total momentum of the system and its quantum numbers. As an argument of the distribution function in the virtual J/ψ meson we use the light-cone variable $\xi_i \equiv \xi_i^+ = (\varepsilon + p_L)/(E_h + P_h)$, where ε, p_L – energy and longitudinal momentum of a parton.

Because of the life-time of the fluctuation with a pair of charmed quarks being much less than the one for the fluctuation, consisting of light partons only, the full quark-gluon cascade cannot develop. This leads to the situation, where the newly created fluctuation with charmed quarks does not practically contain light partons and the pair of heavy quarks carries all the momentum of the virtual J/ψ. Therefore, the probability to observe the Fock state with $c\bar{c}$ pair can be written as follows [2]:

$$dW^{c\bar{c}} = \frac{\xi_c^2\, \xi_{\bar{c}}^2\, \rho_c(\xi_c)\, \rho_{\bar{c}}(\xi_{\bar{c}})}{\left(\xi_c + \xi_{\bar{c}}\right)^2} \delta\left(1 - \xi_c - \xi_{\bar{c}}\right) \frac{d\xi_c}{\xi_c} \frac{d\xi_{\bar{c}}}{\xi_{\bar{c}}}. \qquad (8)$$

In J/ψ meson charmed quarks are the valence quarks. Thus, coming from Regge phenomenology, one can expect, that at small values of the relative momentum the probability density $\rho(\xi)$ can be parametrized as:

$$\rho_c(\xi) = \rho_{\bar{c}}(\xi) = \xi^{\alpha}, \qquad (9)$$

where, $\alpha \approx 0.5$, as in ordinary hadrons. So, the inclusive distribution of the charmed quark in the photon has the form:

$$c^{\gamma}(\xi) = \xi^{\beta}\, (1 - \xi)^{\beta} / B(\beta + 1, \beta + 1), \qquad (10)$$

with $\beta = \alpha + 1$; $B(u, v)$ is beta-function and the charmed quarks distributions are normalized on unity, $\int_0^1 d\xi\, c^{\gamma}(\xi) = 1$. Choosing $\alpha = 0.5$, one obtains $\beta = 1.5$. We shall use this value in our calculations. The value of $\beta = 1.5$ is smaller than, e.g., chosen in [21] for description of spectra of charmed mesons, measured in experiment ZEUS. But in our case the correct form of the distribution of c quarks does not play any significant role since the contribution in the structure function is defined mainly by the value of the total cross section of the parton scattering. Then, the momentum transfers in EMC experiment $Q^2 \leq 80$ GeV^2 practically, are completely in the range, where the perturbative consideration of the production and evolution of c quarks is invalid [20]. Thus, we do not consider QCD evolution of c quarks in the virtual J/ψ meson and we shall use scaling expression (10).

2.3 Charmed structure function in leptoproduction

Due to the fact that the structure function is up to a common factor simply sum of cross sections of the subprocesses, it can be also represented as a sum of contributions of three processes (see (6)):

$$F_2^c(x,Q^2) \;=\; F_2^{IC}(x,Q^2) \,+\, F_2^{PGF}(x,Q^2) \,+\, F_2^{\psi}(x,Q^2)\,. \qquad (11)$$

In framework of parton model the structure function of the "intrinsic charm" F_2^{IC} is connected to the distribution of charmed quarks in the proton $c^p(x,Q^2)$ and is equal to:

$$F_2^{IC}(x,Q^2) \;=\; 2\,N_{IC}\,e_c^2\,x\,c^p(x,Q^2)\,, \qquad (12)$$

where, $x\,c^p(x,Q^2)$ is normalized on unity, $e_c = \frac{2}{3}$ is the electric charge of c quark and N_{IC} defines the level of the admixture of charmed quarks in the proton.

The structure function F_2^{PGF} defines the photon-gluon fusion and is [29]:

$$F_2^{PGF}(x,Q^2) \;=\; \int_{\sqrt{1+4\lambda}\,x}^{1} \frac{d\xi}{\xi}\, G(\xi,Q^2)\, f_2(\frac{x}{\xi},Q^2), \qquad (13)$$

where,

$$\begin{aligned} f_2(z,Q^2) \;&=\; \tfrac{\alpha_s(\hat{s})}{\pi}\, e_c^2\,\pi\, z \Big\{ V_c\,\left[-\tfrac{1}{2} \,+\, 2z(1-z)(2-\lambda)\right] \\ &+\; \left[1-2z(1-z) \,+\, 4\lambda z(1-3z) \,-\, 8\lambda^2 z^2\right] \ln\tfrac{1+V_c}{1-V_c} \Big\}. \end{aligned} \qquad (14)$$

In the above expressions $\hat{s} = Q^2\,(1-z)/z$, $V_c(\hat{s}) = \sqrt{1-\,4\,m_c^2/\hat{s}}$ is the velocity of c quark in the (γg) center of mass system, $\lambda = m_c^2/Q^2$.

The contribution of the virtual J/ψ meson, F_2^{ψ}, in the charmed structure function is being led by the expression (3) and the cross section of the process $J/\psi\,p \to c$ in framework of parton model is:

$$\sigma_\psi \;=\; 2\,\frac{4\pi\alpha}{f_\psi^2} \sum_i \int d\xi_i\, d\xi_c\, G^p(\xi_i)\, c^\gamma(\xi_c)\, \hat{\sigma}_i(\hat{s})\,. \qquad (15)$$

Factor "2" takes into account the scattering both on c and $\bar{c}$ quarks. Index i runs over all partons in the proton, participating in the scattering off the c quark from the photon. Functions $G^p(\xi_i)$ and $c^\gamma(\xi_c)$ describe the momentum distributions of the ith light parton in the proton and c quark in the photon, respectively. The cross section of the scattering of c quark on the parton of the proton $\hat{\sigma}_i(\hat{s})$ depends on the CM energy squared $\hat{s}$. It is known that at presence of non-perturbative effects, like quark masses, parton model is not a covariant one. Thus when performing the integration in (15) it is necessary to choose some reference frame, satisfying the conditions of the applicabilty of parton model. In our case the most suitable reference frame is the center of mass system of the virtual photon and the proton. If we use the light-cone variable ξ^+ the energy squared $\hat{s}$ can be expressed through invariant variables x and Q^2 and is equal to $\hat{s} = m_c^2 + \xi_c \xi_i \, Q^2/x$.

Formulae for the cross sections of the scattering subprocesses $cg \to cg$ and $cq \to cq$ of massive c quarks in the lowest order over α_s can be found in [8, 30]. For the completeness we give these formulae in the Appendix. Pure kinematically the minimal momentum transfer is $\hat{t}_{min} = 0$. Because the cross section of the scattering process is divergent at lower limit of the integration over $\hat{t}$, the first question is, obviously, about the cut-off value $\hat{t}_{min}$. At low momentum transfers pQCD becomes invalid and the value of the cut-off momentum also cannot be calculated theoretically. For the processes with c quarks various choices of $|\hat{t}_{min}|$ are being used, varying from $m_c^2/4$ to m_{cT}^2, where m_{cT}^2 is the transverse mass of c quark squared. We shall consider the value of $\hat{t}_{min}$ as a free parameter, which must be found from experimental data. We use the same value of $|\hat{t}_{min}|$ also in the argument of the strong coupling constant $\alpha_s(|\hat{t}_{min}|)$, because the main contribution in the total cross section is defined mainly by the range $\hat{t} \sim \hat{t}_{min}$.

Since we consider the process $\gamma p \to c\bar{c} + X$ with large momentum transfer, a coalescence of one of the final c quarks with the proton remnant is not probable. Thus, according to quantum numbers conservation, there must be as minimum three particles in the final state – the proton and two D mesons. So, general kinematical restriction for the scattering reaction takes the form (m_D is mass of D meson, m_p is the proton mass).

$$\frac{(1-x)}{x} Q^2 + m_p^2 \;\geq\; (2\, m_D + m_p)^2 \,. \tag{16}$$

At presence of the non-zero cut-off $\hat{t}_{min}$ there are additional kinematic constrains on threshold energies $\sqrt{\hat{s}_{th}}$ [8, 30] for the subprocess. We also give them in Appendix.

It is easy to obtain necessary integration limits in (15), considering the kinematics of the parton scattering. Taking into account non-zero value of $\hat{t}_{min}$ the integration limits over ξ_i and ξ_c are:

$$\begin{array}{lcccc} x\left[1 + \frac{(\sqrt{\hat{s}_{th}}+m_c)^2}{Q^2}\right] & \leq & \xi_i & \leq & 1\,, \\[2ex] \frac{x\,(\hat{s}_{th}-m_c^2)}{\xi_i\, Q^2} & \leq & \xi_c & \leq & 1\,. \end{array} \tag{17}$$

3 Results and conclusion

We fitted the calculated $F_2^c(x, Q^2)$ to EMC data. The charm photoproduction cross section $\sigma(\gamma p)$, measured in [3] has been recalculated to the structure function as described in [2].

Comparing the calculations with data we took into account the next-to-leading order QCD corrections to the "intrinsic charm" structure function F_2^{IC}, as well as non-zero masses of the proton and charmed quark (see [2, 17, 31]). When calculating the contribution of the photon-gluon fusion we used the parametrization MRS(G) for the gluon distribution in the proton from PDFLIB package [32]. The parametrization MRS(G) has been obtained with α_s in the second order and $\Lambda_{QCD} = 0.174$ GeV. We included mass of the c quark in free parameters to check the self-consistency of our calculations.

Fit of EMC data gave the following values of free parameters:

$$N_{IC} = (0.2 \pm 0.2)\% \,, \tag{18}$$

$$m_c = (1.51 \pm 0.03)\ \mathrm{GeV} \,, \tag{19}$$

$$\hat{t}_{min} = (-3.0 \pm 0.3)\ GeV^2 \,,$$

at good value of $\chi^2/NDF = 0.74$. The value of cut-off over the momentum transfer squared is approximately equal to the transverse c quark mass squared, as it could be expected from general considerations. The resulting value $m_c = 1.51 \pm 0.03$ GeV agrees with $m_c = 1.50$ GeV, used in the parametrization MRS(G), which testifies the self-consistency of our approach. The comparison of the model with EMC data [3] is given in Fig.2.

Note the following. In paper [8] the calculations have been performed for the charm excitation mechanism in hadron collisions, i.e., there have been considered the processes of the scattering of partons on the charmed quarks of the proton (on "intrinsic charmed quarks"). The contribution in the charm leptoproduction formed by hadronic component of the photon is completely analogous to the charm excitation in hadron collisions, considered in [8]. In paper [8] the level of the intrinsic charm in the proton has been chosen equal to 0.5% and the conclusion was made that the charm excitation mechanism ensures the needed yield of charmed particles at ISR energies due to steeper rise of the scattering cross section with reaction energy, which allows to agree ISR data and data obtained at lower energies in fixed target experiments. In paper [8] the cut-off momentum transfer has been chosen equal to $\hat{t}_{min} = m_c^2/4 \approx 0.6$ GeV^2, which is considerably less than obtained in present paper.

The results of present paper give significantly less admixture of the intrinsic charm in the proton and much larger value of the cut-off momentum $\hat{t}_{min}$ in the scattering subprocesses. Therefore, the contribution of the charm excitation mechanism in the hadron collisions is, as minimum, order of magnitude less than that obtained in [8] and cannot explain large yield of charmed particles, observed in ISR experiments. Thus, the contradiction between ISR data and data of fixed target experiments is not avoided.

As it follows from the results of present work, it is not necessary to introduce any visible admixture of the non-perturbative charm quarks in the proton to describe EMC data, even when using "soft" gluon distribution. The excess of the EMC data over the photon-gluon predictions at large Q^2 can be completely explained by the contribution of the hadronic component of the photon. In any case, the considered mechanism decreases significantly the discrepancy between EMC data and PGF predictions and, respectively, the admixture of Fock states with charmed quarks in the proton.

On the other hand, we have introduced a non-perturbative charmed component in the photon wave function. The reason, why the photon can have visible non-perturbative component of c quarks in difference to the proton can be understood from result of paper [24], which states that the perturbative regime in the photon starts at $Q^2 \approx 5.5$ GeV^2, and for the proton the DGLAP equations give good description of the evolution of the structure function starting already from $Q^2 \approx (1-2)$ GeV^2. Thus, there is no necessity to introduce the non-perturbative charmed states in the proton and the charm contribution to the proton structure function can be described by pQCD.

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4 Appendix

Expressions for total and differential cross sections of c quark scattering at lowest order of α_s [30] (we write out these formulae as they are given in [8]).

$$
\begin{aligned}
\frac{d\sigma(q\bar{q}\to c\bar{c})}{d\hat{t}} &= \frac{4\pi}{9\hat{s}^2}\,\alpha_s^2(4m_c^2)\,\frac{(m_c^2-\hat{t})^2+(m_c^2-\hat{u})^2+2m_c^2\hat{s})}{\hat{s}^2}\,;\\
\sigma(q\bar{q}\;\to\;c\bar{c}) &= \frac{8\pi}{27\hat{s}}\,\alpha_s^2(4m_c^2)\,\left(\hat{s}+2mc^2\right)\,\sqrt{1-\frac{4m_c^2}{\hat{s}}}\,;\\
\hat{s}_{th} &= 4\,m_c^2\,.
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\sigma(gg\to c\bar{c})}{d\hat{t}} &= \frac{\pi}{16\hat{s}^2}\,\alpha_s^2(4m_c^2)\,\left[\frac{12}{\hat{s}^2}(m_c^2-\hat{t})(m_c^2-\hat{u})+\frac{8}{3}\frac{(m_c^2-\hat{t})(m_c^2-\hat{u})-2m_c^2(m_c^2+\hat{t})}{(m_c^2-\hat{t})^2}\right.\\
&+\;\frac{8}{3}\frac{(m_c^2-\hat{t})(m_c^2-\hat{u})-2m_c^2(m_c^2+\hat{u})}{(m_c^2-\hat{u})^2}\;-\;\frac{2m_c^2(\hat{s}-4m_c^2)}{3(m_c^2-\hat{t})(m_c^2-\hat{u})}\\
&-\;\left.6\,\frac{(m_c^2-\hat{t})(m_c^2-\hat{u})+m_c^2(\hat{u}-\hat{t})}{\hat{s}(m_c^2-\hat{t})}\;-6\,\frac{(m_c^2-\hat{t})(m_c^2-\hat{u})+m_c^2(\hat{t}-\hat{u})}{\hat{s}(m_c^2-\hat{u})}\right]\,;\\
\sigma(gg\;\to\;c\bar{c}) &= \frac{\pi}{3\hat{s}}\,\alpha_s^2(4m_c^2)\,\left[-\frac{1}{4}\left(7+\frac{31m_c^2}{\hat{s}}\right)\,x+\left(1+\frac{4m_c^2}{\hat{s}}+\frac{m_c^4}{\hat{s}^2}\right)\,\log\frac{1+x}{1-x}\right],\\
x &= \sqrt{1-\frac{4m_c^2}{\hat{s}}};\;\;\hat{s}_{th}\;=\;4\,m_c^2\,.
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\sigma(qc\to qc)}{d\hat{t}} &= \frac{4\pi}{9(\hat{s}-m_c^2)^2}\,\alpha_s^2(-\hat{t}_{min})\,\frac{(m_c^2-\hat{u})^2+(\hat{s}-m_c^2)^2+2m_c^2\hat{t}}{\hat{t}^2}\,;\\
\sigma(qc\;\to\;qc) &= \frac{4\pi}{9(\hat{s}-m_c^2)^2}\,\alpha_s^2(-\hat{t}_{min})\,\left[\left(1-\frac{2\hat{s}}{\hat{t}_{min}}\right)\left(\frac{(\hat{s}-mc^2)^2}{\hat{s}}+\hat{t}_{min}\right)-2\hat{s}\log\frac{(\hat{s}-m_c^2)^2}{-\hat{t}_{min}\hat{s}}\right]\,;\\
\hat{t}_{min} &= 0;\;\;\hat{t}_{max}\;=\;-(\hat{s}-m_c^2)^2/\hat{s}\,;\\
\hat{s}_{th} &= m_c^2\;-\;\frac{1}{2}\,\hat{t}_{min}\;+\;\left(-m_c^2\,\hat{t}_{min}\;+\;\frac{1}{4}\,\hat{t}_{min}^2\right)^{1/2}\,.
\end{aligned}
$$

$$
\begin{aligned}
\frac{d\sigma(gc\to gc)}{d\hat{t}} &= \tfrac{\pi}{16(\hat{s}-m_c^2)^2}\,\alpha_s^2(-\hat{t}_{min})\ \Big[\tfrac{32(\hat{s}-m_c^2)(m_c^2-\hat{u})}{\hat{t}^2} \\
&+ \tfrac{64}{9}\tfrac{(\hat{s}-m_c^2)(m_c^2-\hat{u})+2m_c^2(\hat{s}+m_c^2)}{\hat{s}-m_c^2)^2} + \tfrac{64}{9}\tfrac{(\hat{s}-m_c^2)(m_c^2-\hat{u})+2m_c^2(\hat{u}+m_c^2)}{m_c^2-\hat{u})^2} \\
&+ \tfrac{16}{9}\tfrac{m_c^2(4m_c^2-\hat{t})}{(\hat{s}-m_c^2)(m_c^2-\hat{u})} + 16\,\tfrac{(\hat{s}-m_c^2)(m_c^2-\hat{u})+m_c^2(\hat{s}-\hat{u})}{\hat{t}(\hat{s}-m_c^2)} \\
&- \quad 16\,\tfrac{(\hat{s}-m_c^2)(m_c^2-\hat{u})-m_c^2(\hat{s}-\hat{u})}{\hat{t}(m_c^2-\hat{u})}\Big]\ ; \\
\sigma(gc\,\to\,gc) &= \tfrac{\pi}{(\hat{s}-m_c^2)^2}\,\alpha_s^2(-\hat{t}_{min})\ \left[\left(1+\tfrac{4}{9}\left(\tfrac{\hat{s}+m_c^2}{\hat{s}-m_c^2}\right)^2\right)\ (\hat{t}_{min}-\hat{t}_{max})\right. \\
&+ \tfrac{2}{9}\tfrac{\hat{t}_{min}^2-\hat{t}_{max}^2}{\hat{s}-m_c^2} + 2(\hat{s}+m_c^2)\log\tfrac{\hat{t}_{min}}{\hat{t}_{max}} \\
&+ \tfrac{4}{9}\tfrac{\hat{s}^2-6m_c^2\hat{s}+6m_c^4}{\hat{s}-m_c^2}\log\tfrac{\hat{s}-m_c^2+\hat{t}_{min}}{\hat{s}-m_c^2+\hat{t}_{max}} + 2\,(\hat{s}-m_c^2)\left(\tfrac{1}{\hat{t}_{max}}-\tfrac{1}{\hat{t}_{min}}\right) \\
&+ \left.\tfrac{16}{9}\,m_c^4\ \left(\tfrac{1}{\hat{s}-m_c^2+\hat{t}_{max}} - \tfrac{1}{\hat{s}-m_c^2+\hat{t}_{min}}\right)\right]\ ; \\
\hat{t}_{max} &= -\max\left(\hat{s}-m_c^2+\hat{t}_{min},(\hat{s}-m_c^2)/\hat{s}\right)\ , \\
&\quad \left(\text{to enforce } \hat{u}-m_c^2\,<\,\hat{t}_{min}\right)\ ; \\
\hat{s}_{th} &= \begin{cases} m_c^2-\frac{1}{2}\hat{t}_{min}+\left(-m_c^2\,\hat{t}_{min}\,+\,\frac{1}{4}\hat{t}_{min}^2\right)^{1/2}\ , & \text{if } -\hat{t}_{min}\ <\ \frac{1}{2}m_c^2\,; \\ m_c^2\,-\,2\,\hat{t}_{min}\,, & \text{if } -\hat{t}_{min}\ >\ \frac{1}{2}m_c^2\,. \end{cases}
\end{aligned}
$$

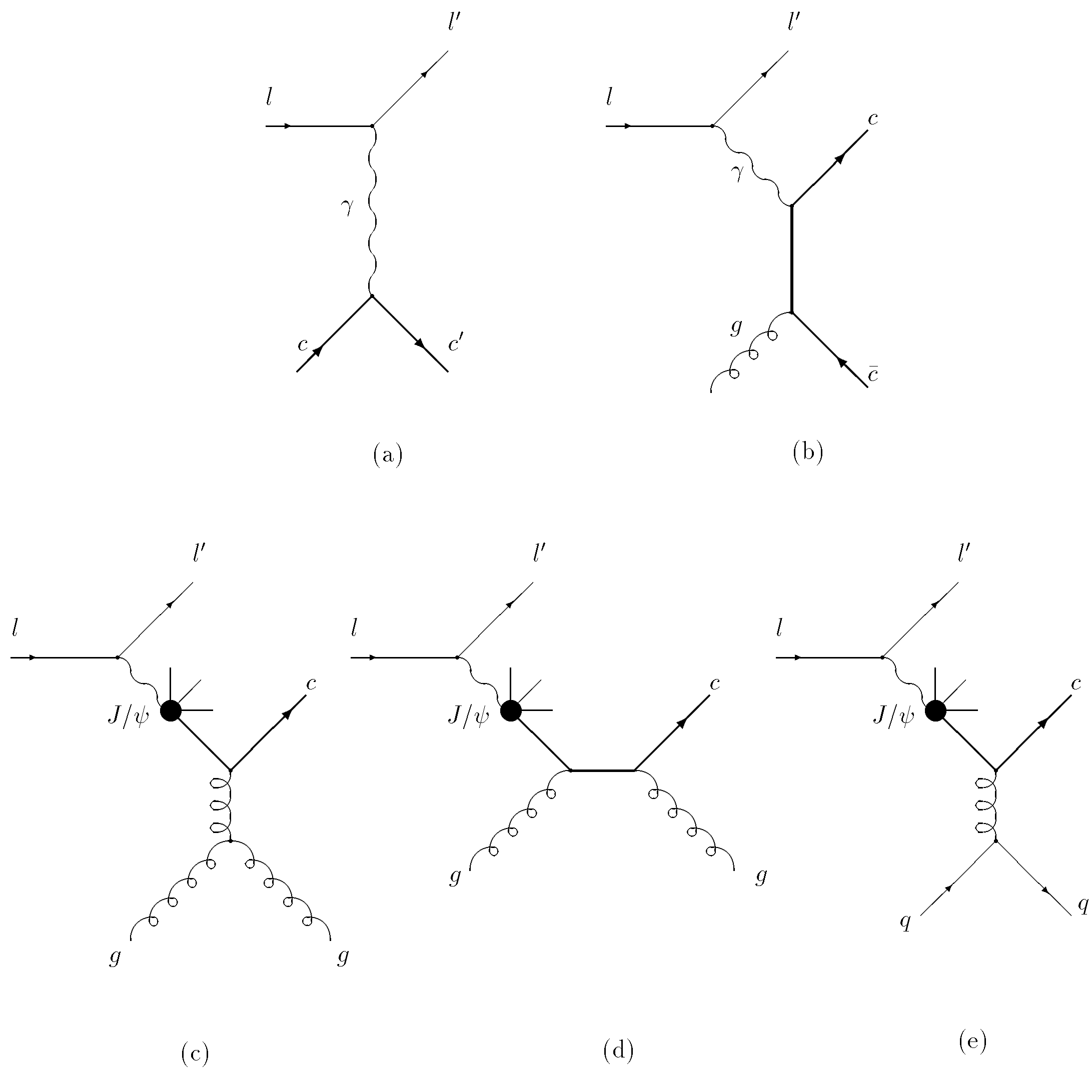

Figure 1: Processes considered in present paper and giving a contribution in structure function of the charm leptoproduction: (a) — the lepton scattering off c quark (the radiative corrections are not depicted); (b) — photon-gluon fusion; (c), (d), (e) — the scattering of c quark from the photon on gluon and quark from the proton, respectively.

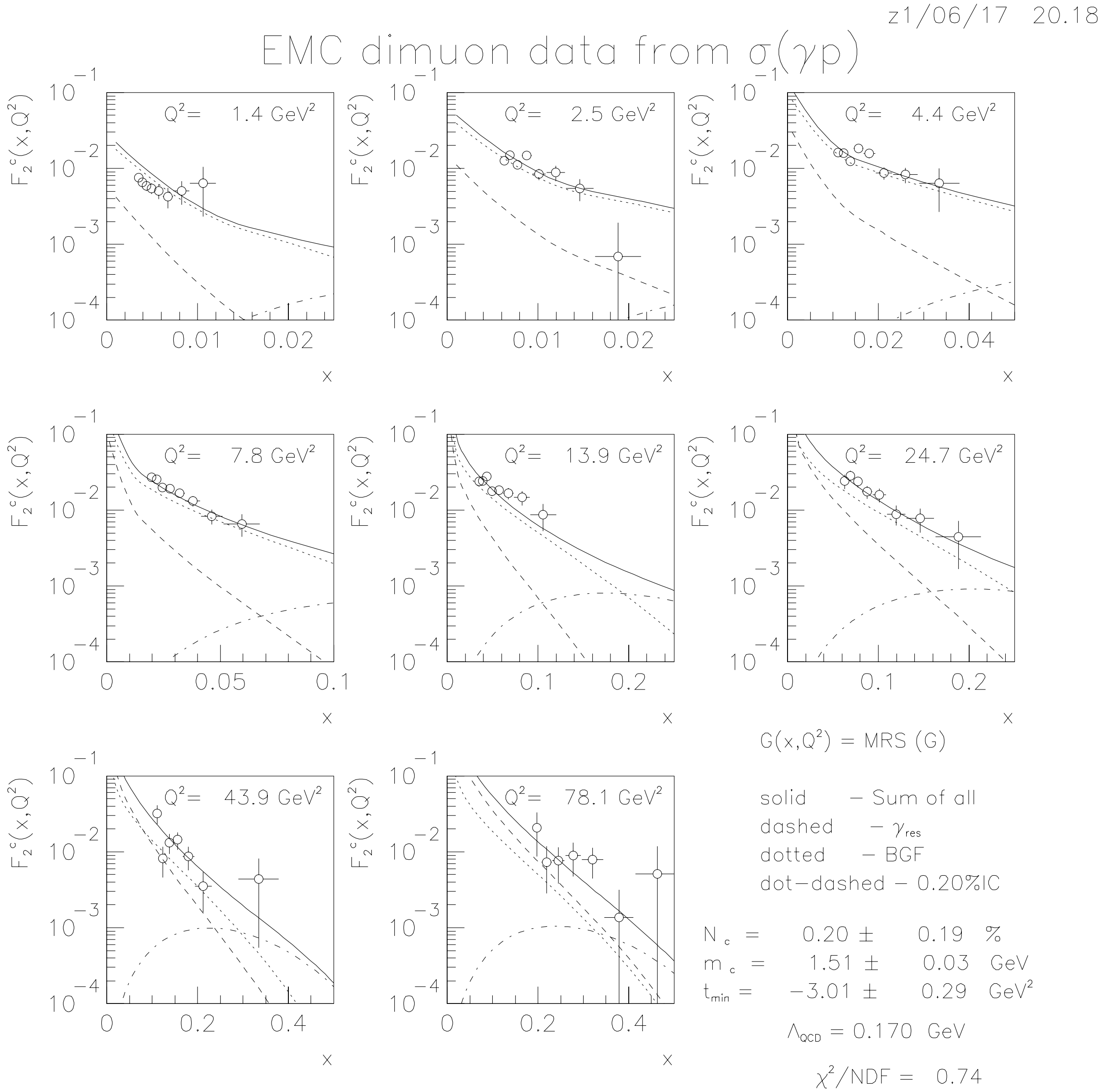

Figure 2: A comparison of the result obtained in present work with experimental data of EMC. Solid line – sum of all contributions, dashed line – the contribution of the hadronic component of the photon, dotted line – PGF, dot-dashed line – the scattering of the point-like photon on c quark from the proton ("intrinsic charm"). For the gluon distribution the parametrization MRS(G) was used. The results are given for the following values of the parameters: $\hat{t}_{min} = -3.01$ GeV^2, $N_{IC} = 0.20\%$ and mass of c quark $m_c = 1.51$ GeV.